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The LXeCAT Instrument for Gamma-Ray Astrophysics

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Abstract. The Liquid Xenon Coded Aperture Telescope (LXeCAT) and its capability to image astrophysical γ-ray sources in the MeV region is described. The γ-ray detector is a Liquid Xenon Time Projection Chamber (LXe-TPC) triggered by the primary scintillation light. Effective background rejection is a direct consequence of the intrinsic three-dimensional imaging capability of the LXe-TPC. Initial results with a 10 liter prototype confirm an energy resolution of 6% FWHM, a position resolution of 1 mm RMS and a light triggering efficiency higher than 90% for 1 MeV γ-rays.

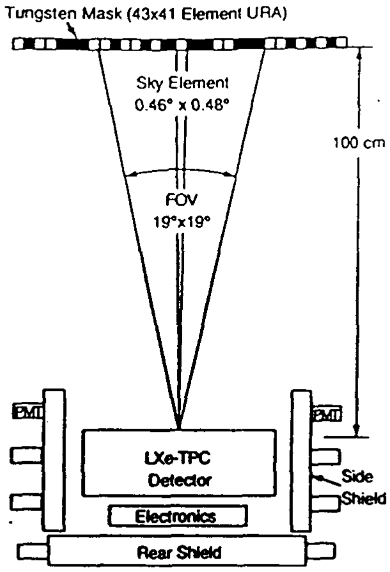
Key words: gamma-rays, imaging

1. Introduction

As initial application of the liquid xenon detector technology for gamma-ray astrophysics, we have proposed (Aprile et al. 1992a) a telescope design which combines a liquid xenon time projection chamber (LXe-TPC) as 3-D position sensitive detector with a coded aperture mask (Figure 1). The telescope is optimized for the MeV energy region (0.3-10 MeV). The angular resolution is 0.5° over a 19° × 19° FOV (FWHM). The point source location accuracy is 2 arcminutes for a 10 sigma source, based on the submillimeter spatial resolution of the LXe-TPC and its excellent background rejection capability. The LXe-TPC sensitive area is 35 cm × 35 cm. With an active liquid xenon layer of 10 cm ($Z = 54$, density $= 3.06$ g cm^{-3}) the full energy peak detection efficiency is 65% at 1 MeV.

For background reduction at balloon altitude, a 5 cm thick CsI active anticoincidence shield surrounds the LXe detector. Figure 2 shows the calculated total background spectrum and its individual components at 3 g cm^{-2} over Palestine, TX. The 3-D imaging capability of the LXe-TPC permits background reduction over the entire energy range of interest. A fiducial volume selection can be used to reject β^--decays and other localized events from activation, as well as low energy γ-rays from shield leakage which are readily photoabsorbed within a few centimeters of the LXe active volume. At MeV energies, where Compton scattering dominates, background γ-rays can be identified through an analysis of the Compton kinematics (Aprile et al. 1993). The TPC measures not only the ionization but also the primary scintillation light signal associated with each ionizing event. The strong dependence of the light pulse shape on the event's ionization density offers an additional background rejection capability through pulse shape discrimination.

The 3σ minimum flux sensitivity of the LXeCAT instrument is shown on Figure 3. The sensitivity curves of the other instruments have been taken from Winkler 1991. With a typical high-altitude balloon observation of the Crab Nebula region for 10 hr, the significance of the image will be 16σ in the range 0.5–1 MeV and 11σ in the range 1–10 MeV. Since a point source can be located with a precision of $\sigma_{loc} = \sigma_{pixel}/n_\sigma$ and the characteristic size of a pixel is about 30′, the uncertainty in the Crab Neb-



Energy Range	0.3 - 10 MeV
Energy Resolution	6% FWHM at 1 MeV
3-D Spatial Resolution	< 1 mm
Geometrical Area	~1200 cm^2
Active Shield	5 cm CsI
FOV	19° x 19° FWHM
Angular Resolution	30 arcmin
Point Source Location Accuracy	~2 arcmin(10σ source)

Fig. 1. Schematic view of the Liquid Xenon Coded Aperture Telescope (LXeCAT).

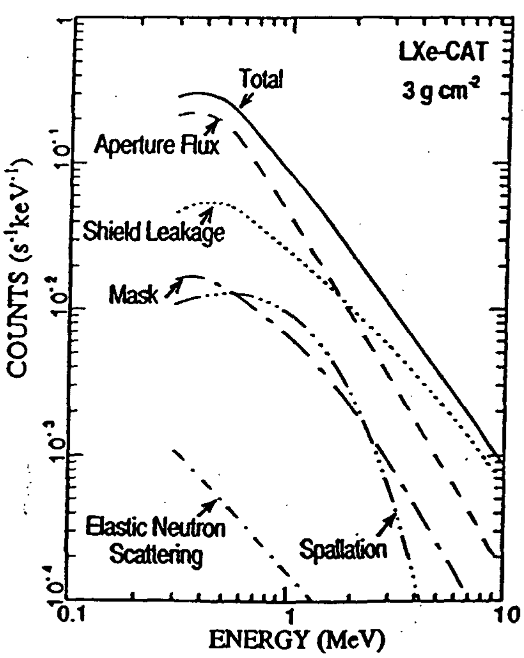


Fig. 2. Estimated background rate for LXeCAT at balloon altitude.

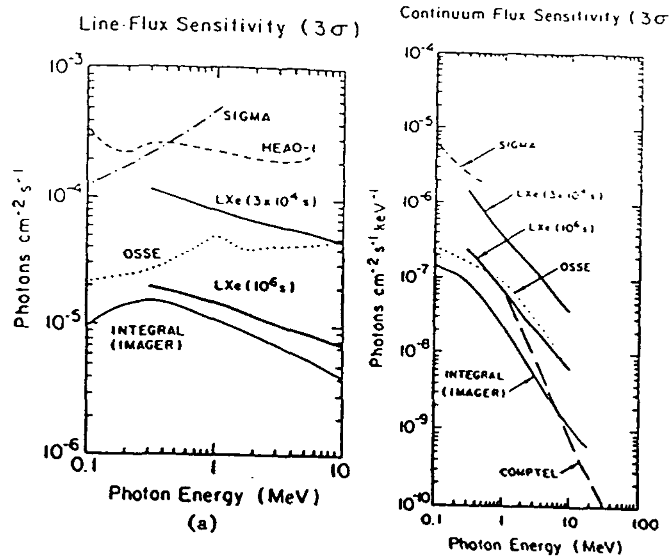


Fig. 3. Estimated LXeCAT 3σ line and continuum sensitivity.

ula location for this observation would be about 2′. The sensitivity of the LXe-TPC as Compton polarimeter has also been studied (Aprile et al. 1994a).

The measurement of the ^{26}Al distribution in the Galaxy via the 1.809 MeV γ-ray line is one of the science objectives of the LXeCAT (Aprile et al. 1995). We estimate that LXeCAT can see the ^{26}Al Galactic center "hot spot" (Diehl et al. 1994) with a significance of 6σ, given a long duration balloon (LDB) flight of about 30 days (Grindlay et al. 1995), with half the time "on source".

2. The LXe-TPC as γ-ray spectrometer and imager: results with a 10 liter prototype

The LXe-TPC measures the energy and the spatial distribution of each ionizing event occurring within the active volume, using both the charge and the primary scintillation light signature. LXe is an efficient ionizer and an excellent scintillator, with a yield similar to that of NaI(Tl) and a fast (< 10 ns) time response. The light signal provides an ideal trigger to mark the time origin of a γ-ray interaction in the TPC. The drift of ionization electrons in a uniform electric field induces a charge signal on sensing electrodes. To image the ionization electrons produced by γ-ray interactions inside the liquid xenon, we have proposed the system of sensing electrodes shown in Figure 4. It consists of two orthogonal sense wire planes, separated from the drift region by a screening wire grid. The positions of the wires hit give the $X - Y$ coordinates of the electron image. The drift time measured with respect to the scintillation light trigger, plus the known drift velocity, gives the Z-coordinate information. The charge collected with a plate anode placed below the wire structure, gives the total event energy. For γ-ray events with multiple

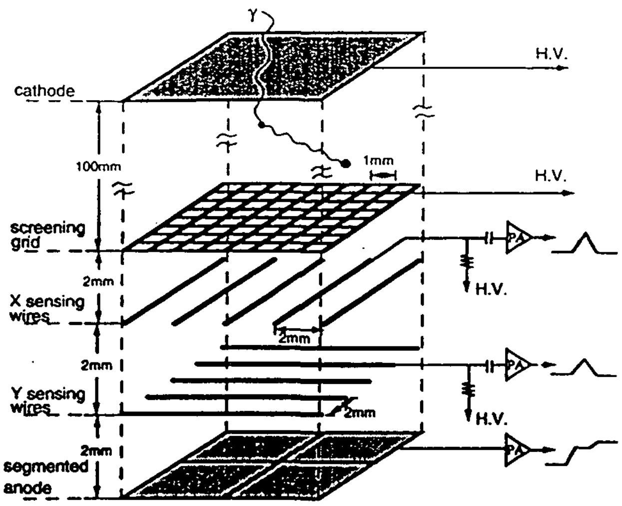
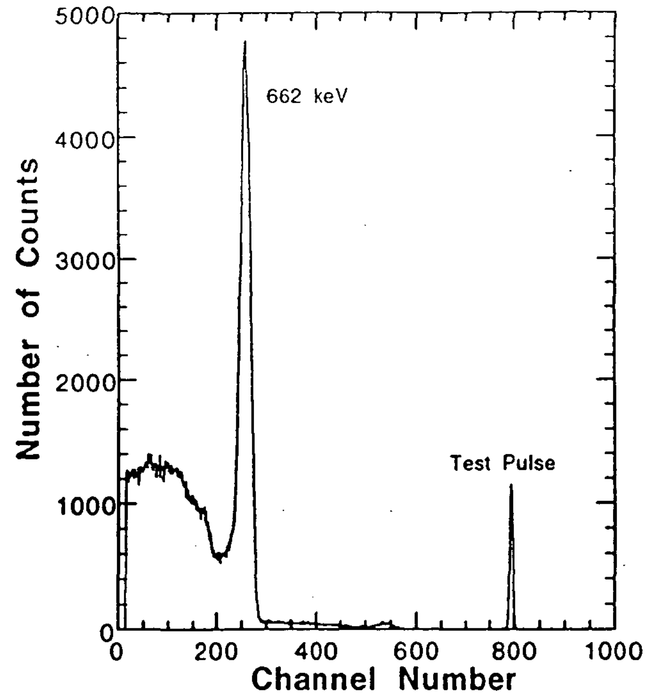


Fig. 4. The electrodes system of the 3-D LXe-TPC



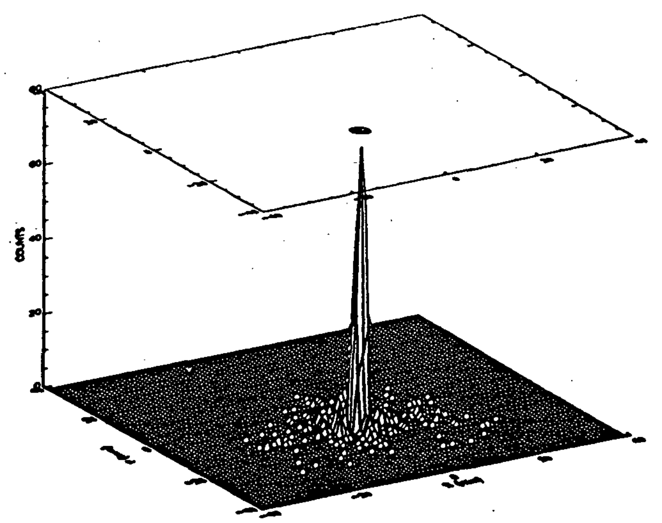


Fig. 5. Energy spectrum (a, top) and Spatial distribution (b, bottom) of a collimated ^{137}Cs 662 keV γ-ray source. The collimator diameter is 2 mm.

Compton interactions, the anode signal has a characteristic multi-step signature. The height of each step is proportional to the energy liberated in each interaction point, and the time interval between the steps is proportional to the relative distance, along the Z-direction, between the interaction points. The sum of all the step pulse heights is proportional to the total energy of the original γ-ray, if it is totally absorbed. The factors which determine the ultimate energy and spatial resolution of a liquid xenon chamber have been studied by our group (Aprile et al. 1991, 1992b).

To demonstrate the operation of a large volume liquid xenon detector for γ-ray spectroscopy and 3-D imaging we have built and are currently testing a 10 liter LXe-TPC prototype, implemented with the electrode system discussed above. The drift gap is 5 cm and the active area is 20 cm × 20 cm. To detect the xenon primary scintillation light and measure its efficiency as trigger signal, a 5 cm diameter UV sensitive PMT, coupled to the TPC vessel via a quartz window, is used. Experiments have been carried out to test the cryogenics operation, the level of liquid xenon purity (which affects charge collection and thus energy resolution) and the response to various γ-ray sources. Figure 5 (a, b) show the energy spectrum and the reconstructed image of 662 keV γ-rays from a ^{137} Cs source collimated with a 2 mm diameter hole. The data are consistent with a detector RMS spatial resolution of about 1 mm and a FWHM energy resolution of 6.7% for 662 keV, at a drift field of 4 kV/cm.Improved energy resolution has been measured with a smaller chamber filled with liquid xenon doped with a photosensitive material (Aprile et al., 1994b). The scintillation light signal produced by 662 keV γ-ray interactions in LXe was also detected and used to trigger the charge signal (see Fig. 6). The light trigger efficiency at 662 keV is higher than 90%.

The capability of a LXe-TPC as Compton telescope (Aprile et al. 1989) has also been studied. 1.274 MeV γ-rays from a parallel ^{22}Na source-beam, showing a single Compton scattering followed by a photoabsorption were selected for this analysis. Figure 7 shows the on-line display of such an event recorded with the 10 liter LXe-TPC. The magnified view of the digitized anode pulse clearly shows the selected event topolgy. The sum of the two steps pulse heights corresponds to the total energy of 1.274 MeV. From the time and amplitude analysis of the induction and collection signals, the coordinates and the energy for the two interaction points are inferred as well as their spatial separation. The most probable scattering angle is then found from the kinematics of the Compton scattering process.

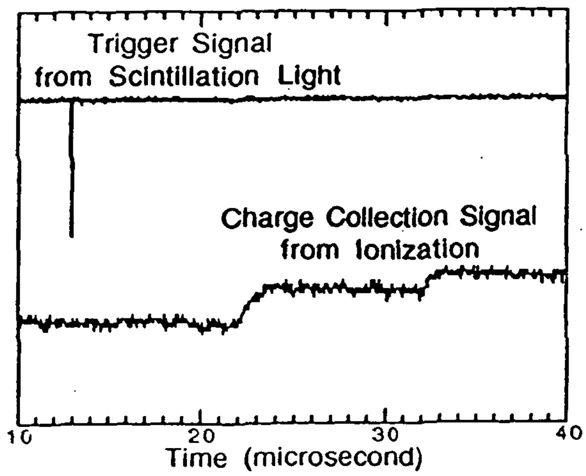


Fig. 6. Charge collection signal triggered by the primary scintillation light for a 662 keV Compton scattering event.

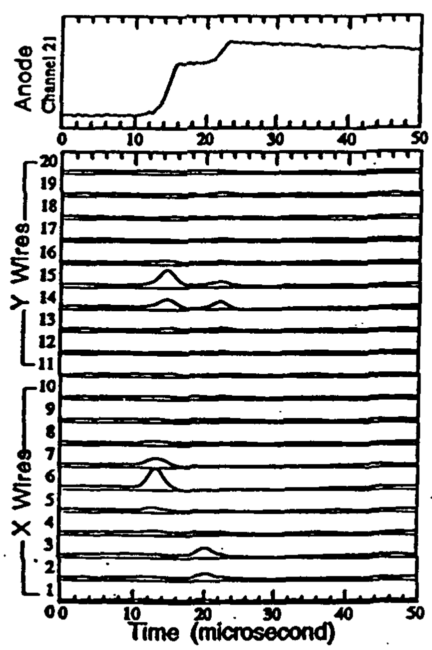


Fig. 7. Charge collection and induction signals recorded for a 1.274 MeV Compton scattering event

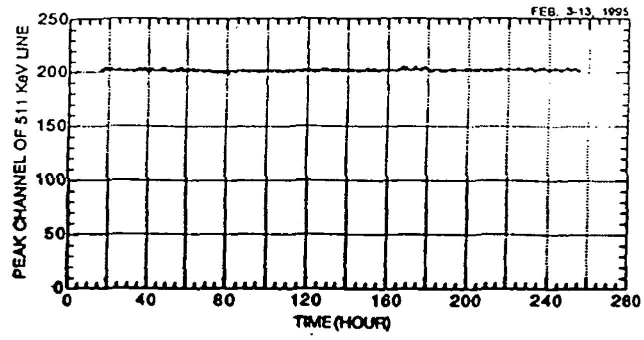


Fig. 8. Time stability of LXe-TPC charge signal

Finally, the time stability of the charge signal has been verified for a period of 10 days. In Fig. 7 the peak channel of the 511 keV line from ^{22}Na is plotted as a function of time, showing a constant signal to within 0.5%.

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